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DESIGN OF VENTILATED CLOTHING

PAUL WEBB, M.D.
E. K. KLEMM

AERO MEDICAL LABORATORY

MARCH 1959

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FOREWORD

The subject matter of this report has been accumulated over a period of several years and under several projects and tasks of the Aero Medical Laboratory. Development of ventilating systems was originally carried under Project No. 6330, "Air Conditioned Anti-Exposure Suit," then under Project No. 6333, "Development of Pressure Suit Systems," Task No. 63622, "Development of Pressure Suit Ventilation." It is currently under Project No. 7164, "Physiology of Flight," Task No. 71831, "Personal Protection for Extreme Altitude Operations." Physiological evaluation was first carried under Project No. 7155, "Human Thermal Tolerance," and is currently under Project No. 7164, Task No. 71830, "Human Thermal Stress in Extended Environment."

All developments and tests referred to in the text were carried out as in-house activity by the Environment Section, Physiology Branch, Aero Medical Laboratory. Most members of the Environment Section have at various times contributed to the evolution of the present design of ventilating garments. Acknowledgement of these significant contributions is made collectively.

ABSTRACT

The purpose of ventilation of clothing is reviewed and the functions of convective and evaporative cooling are described. How to achieve these functions is discussed in detail by describing the principles of proper air distribution, effective evaporation, and full utilization of convective cooling in ventilated clothing assemblies. A description of various ventilating garments is given to illustrate the evolution of principles, and, finally, an "ideal" ventilating system is defined for the difficult problem of ventilated pressure suit assemblies. Tests are described which demonstrate the validity of employing each of the design principles which go into the "ideal" system. The general subjects of low energy ventilating systems and of integration of ventilated clothing assemblies are discussed. Recommendations are made concerning the use and design of ventilation systems for protective clothing.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMAND

ANDRES I. KARSTENS
Colonel, USAF (MC)
Ass't. Chief, Aero Medical Laboratory
Directorate of Laboratories

INTRODUCTION

Ventilated clothing has been developed in both the Air Force and Navy in recent years and there is a growing literature attesting to its value.[1-6] However, it is not the purpose of this report to review the value of ventilation. Rather, the intent here is to describe certain principes which have been developed in the design of ventilating systems.

Ventilated clothing is any type of garment assembly in which air or other ventilating gas is delivered to the clothing for the purpose of cooling. The technique of ventilation has been especially helpful when used with protective clothing which is common to flying. In military aviation, heavy clothing, which is intended to protect the wearer against arctic cold, may be worn when the wearer is actually in a tropical or desert environment, since a flight may originate in any part of the world and pass through many different areas. This heavy clothing is effectively impermeable to the transfer of water vapor and can be a serious burden in heat.[7] Other types of impermeable clothing are: protective suits for fuel handlers who work at missile sites, decontamination suits as used in chemical warfare, anti-exposure suits used to protect against cold-water immersion, and the several varieties of aircraft pressure suits—both partial-pressure and full-pressure designs. Rubberized cloth or plastic layers in these garments completely or partially block the escape of water vapor. Sweat produced by the man in response to heat would be ineffective if ventilation were not used to evaporate it.

This report presents design principles as they have developed at the Aero Medical Laboratory, and shows how empirical tests have validated each of the principles detailed. Some of these principles may appear obvious to the reader; however, all are presented because each one has been violated, at some time, with serious decrease in effectiveness of the ventilating garment. In other words, the principles which will be presented are hard-won through experience. If applied intelligently, they should lead to effective ventilating garments in future protective clothing.

FUNCTIONS OF VENTILATING AIR

The purpose of ventilating air is to cool the wearer. Cooling is accomplished both by evaporation of moisture and by convection. Convective cooling, the change in temperature between the supply and the exhaust air, is efficient, but the amount of cooling which can be achieved with reasonable airflows is comparatively small. This results from the low specific heat of air. In order for much cooling to be done convectively, a rather large quantity of air must be delivered, and there must be a sizable temperature difference between the cool air supplied and the warm air escaping. On the other hand, evaporative cooling is an effective way of losing large amounts of heat from the body using reasonable flows of dry air. Man's primary defense against heat exposure is through the secretion of sweat. But sweating alone without evaporation is useless as far as cooling is concerned. A major function of ventilating air is to insure evaporation.

Effective cooling occurs at or near the skin. If cooling of the clothing rather than of the body surface occurs, this may be of some help by reducing the convective transfer of heat from the environment. However, some of this convective cooling is essentially wasted by being applied to the air of the room. We can assume that the heat load in a hot room or aircraft cockpit is so great that this amount of room cooling is insignificant.

Uniform distribution of air over as much of the body surface as possible is important. The reason for this is that convective cooling should occur over a wide body surface to avoid local cold spots. Furthermore, it is important to distribute dry air over a large body surface so that evaporation over a wide area will occur. If all dry air is delivered to one point and allowed to escape without reaching the whole body, much of the sweat produced in response to heat would have no chance to evaporate.

Not only must the air arrive and be distributed in an easy and uniform way, it must also be re-collected and allowed to escape uniformly and easily. It has been learned that careful attention must be paid to the escape or return pathways for ventilating air; otherwise, the effectiveness of a well-designed supply system is seriously reduced.

ACHIEVING GOOD FUNCTION

Several principles are explained below which have been helpful in achieving the functions of ventilation.

PRINCIPLES OF AIR DISTRIBUTION

There are certain important dangers to be avoided in designing the air distribution system for ventilated clothing. These dangers are (a) short circuit pathways for air, (b) high-resistance pathways in local spots or small body areas, and (c) blind pockets—for example, an arm where there is no exit for ventilating air. Each of these dangers, when stated in this fashion, appears fairly obvious and should be easy to avoid. Let us, however, examine this subject in more detail.

For the sake of discussion, consider a clothing assembly which is ventilated by means of air delivered through a single inlet and which escapes from the clothing at a single outlet point. Air is distributed from the inlet to cover a wide area of the body. In effect, there is a manifold at the inlet, from which the air is distributed in parallel pathways. When the ventilating air has performed its job of cooling, it is re-collected in an exit manifold before escaping.

If flow of air is to be equal in each of the parallel pathways which exist between inlet and outlet, then each of these parallel pathways must have an equal resistance to airflow. This can be visualized in a simple electrical analogy. In figure 1, electrical current is flowing from A to B through the four resistances in series. If each of the four resistances shown has the same value, then current flow will be equal in each branch circuit.
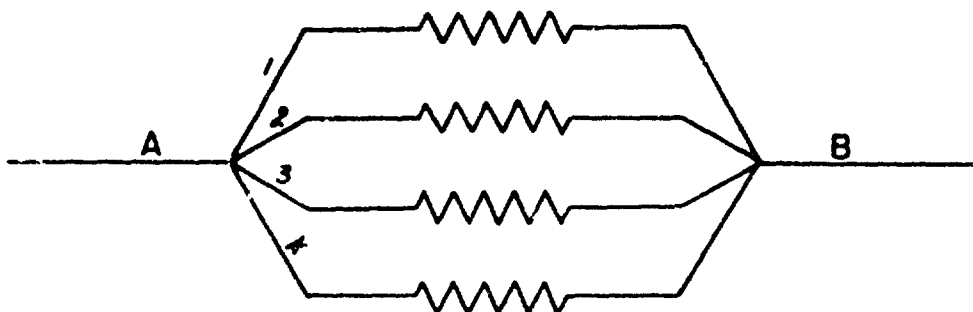

Figure 1. An electrical analogue of distribution of ventilating air between inlet and outlet of the suit system. Current flow and airflow would be equivalent.
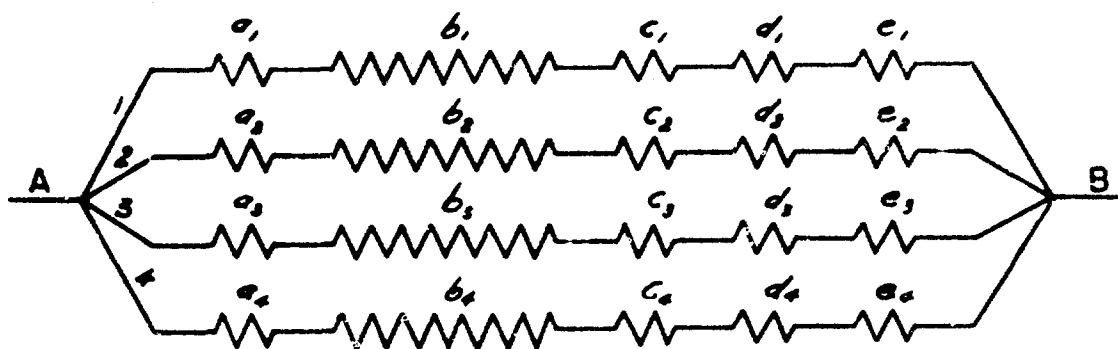
Figure 2. More complete electrical analogue of distribution of
ventilating air between inlet and outlet of the suit system.

Actually each parallel pathway in our air distribution system has not one, but several resistances in series. Going back to the electrical analogy, this may be represented as shown in figure 2. In this circuit, the goal of equal flow in each of the four branch circuits can be met only by having the total of the resistances in series (a, b, c, d, and e) equal to the total resistance in each other branch. This can be done by matching all the resistances at "a" in each of the branch circuits, all the resistances at "b," and so forth. It can also be done by varying any of the single resistors until the total resistance in that branch is equal to the total in the other branches.

The resistances at "b," corresponding to the small delivery holes in the inner layer of the typical Air Force ventilating garment, are very large compared to the other resistances. These resistances at point "b" are not only large, but also equal, since the size of the small hole through which the air has to travel is carefully controlled in the manufacture of this ventilating suit. The effect of this large resistance is to swamp the small resistances before and after it such that, as long as the other resistances are indeed small, any variations between them will be of minor importance. In this way, the principle of equal resistances in the branch circuits is met.

There is another way to picture the distribution of ventilating air in a complete suit assembly. It is possible to imagine the ventilating air moving in layers or sheets, concentrically placed. Surrounding the man and within the clothing assembly there are: the supply layer of ventilating air moving through the ventilating garment, another layer of air next to the skin, and finally the layer of exhaust air moving toward the outlets. It is useful to keep in mind this picture of moving sheets of air, one above the other, and to keep in mind also the resistances as described in earlier paragraphs, which must be adjusted to keep flow uniform within these moving sheets.

EFFECTIVE EVAPORATION

To be sure of evaporation, air must be delivered to the wet skin in a positive way. It has been found that simply sending air to an area of body surface and letting it drift out is not sufficient to insure effective evaporation. Two approaches have been tried to enhance this vital process.

The first approach consisted of delivering most of the ventilating air to domed spaces over the skin. The air came into these spaces in multiple, fine, high-velocity jets. Turbulence from the jets was the object, in order to improve mass transfer (evaporation) and convective heat transfer

The second approach was to bring the inner layer of a double-layered ventilating garment against the skin or underwear, and make the air leaving the delivery holes creep slowly through before being exhausted. The aim was to avoid domes, wrinkles, or folds where air could pass to the exhaust layer before becoming moisture laden. This approach has proved to be better for most uses.

Use of the slow-creep approach brought a special problem involving the potential blockage of the small delivery holes in the inner layer. Wherever the inner layer was pressed against skin or wet underwear, the small holes could block in that area and air would escape more easily elsewhere. This led, of course, to uneven air distribution. Several materials were obtained to relieve blockage by use of the correct surface. Results of tests are shown in figure 3. These tests utilized material samples made in double layers as used in the AF ventilating garment. Two smooth materials and two rough-surfaced materials were tried. In the test arrangement, the amount of blockage was determined when the layer containing small holes was pressed against a smooth plastic sheet, or against a smooth plastic sheet covered with light cotton underwear. A diagram of the test arrangement is shown in the lower right corner of figure 3. Resistance in inches of water is shown in each of the graphs as a function of airflow in cubic feet per minute. The dotted lines marked "blower" indicate the airflow which would occur if one were to use an Air Force blower of radial fan type, which delivers 14 cubic feet against no back pressure. The two lines labeled "wet" and "dry" refer to underwear, either wet or dry, covering the plastic surface. As a result of these tests the "basket-weave" vinyl material was adopted as the material of choice in making the double-layer Air Force ventilating garments. The term basket-weave is used to denote a fine pattern of criss-crossing ridges which is embossed onto the vinyl film before it is fashioned into a ventilating garment.
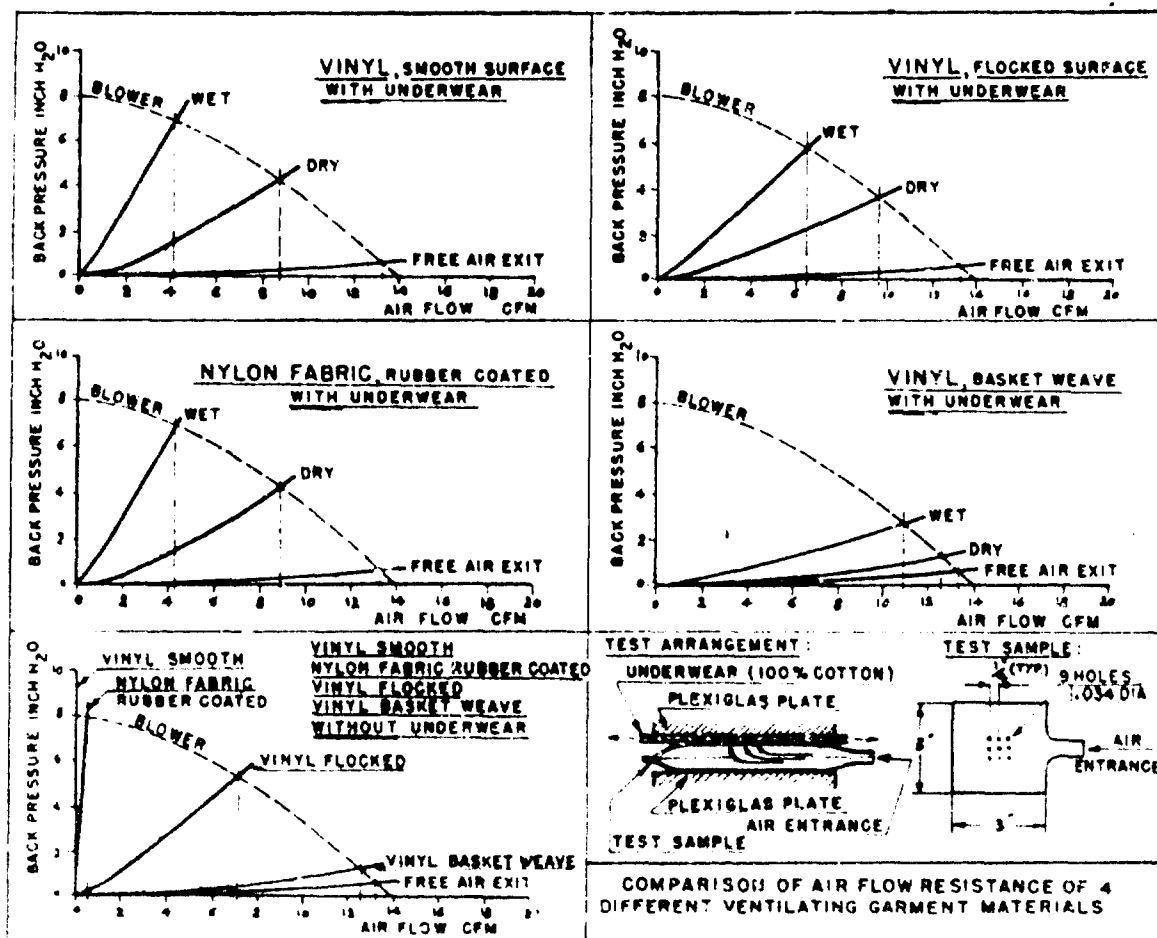

Figure 3. Resistance to flow for several materials fashioned to simulated usage in a ventilating system.

FULL REALIZATION OF CONVECTIVE COOLING

It was pointed out earlier that convective cooling is less important in ventilated clothing than is evaporative cooling, since air and similar gases have low specific heats. As soon as air passes a surface of different temperature, it very quickly acquires the temperature of that surface. In a ventilating suit assembly, air is spread out in a thin sheet and so is in intimate contact with a large surface. It is not surprising that convective cooling, what there is of it, is efficient. Empirical validation of this efficiency was derived in a previous report.[1]

Since convective heat transfer to the ventilating air is essentially complete, it is important to use it for cooling the man. By this is meant that the convective cooling should not take place in outer layers of a clothing assembly, because there may then be a certain amount of cooling, not of the man, but of the surrounding room or cockpit. The hot, surrounding space may be considered an infinite heat source.

The relative location of each of the several sheets of ventilating air as described in the previous section is important. If the sheet of exhaust air can be placed external to other layers, a considerable theoretical advantage is achieved. This is basically like a counterflow heat exchanger. Exhaust air is exposed to the external heat load, and thus gains the highest possible temperature before leaving the system. It has already cooled the man directly. This layer of exhaust air acts as a buffer to absorb external heat before that heat reaches the supply layer of ventilating air. This is shown schematically in figure 4. Achieving this in an actual suit is accomplished by having the exhaust air collect external to the ventilating garment proper before it travels to the outlet. Thus, the large holes visible in figures 6 and 8 serve the important purpose of permitting moisture-laden exhaust air to travel external to the other two layers, where it can pick up extra heat coming in from the environment.
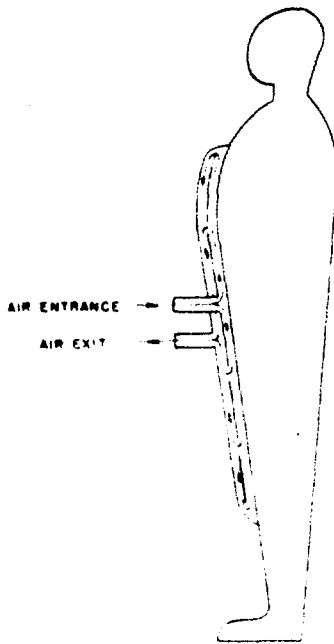

Figure 4. Schematic representation of the principle of the counterflow heat exchanger in ventilated clothing systems.

Finally, the subject of insulation in ventilated clothing, while perhaps not properly a part of the discussion of the movement of ventilating air, has an important bearing on the effectiveness of convective cooling. Most clothing assemblies as used in the Air Force include a certain amount of insulation. The question has been where to locate the layer or layers of insulating material.

Insulation in clothing is used to isolate, in a thermal sense, the man from his environment. In nonventilated clothing, the location of the insulation layer is not particularly critical. In the case of ventilated clothing, however, it must be obvious that insulation should be placed external to the supply layer of ventilating air. The placement of insulation in relation to the exhaust air is a matter of choice which can be influenced by other factors. If the insulation and the return sheet of air are common—that is, if the return air moves through a porous insulation layer—it would seem that the effectiveness of the insulation should be hampered. (However, this arrangement was successfully employed in the early versions of ventilated, anti-exposure suits.) If the insulation is placed below the return layer then the counterflow, heat-exchanger principle is being met. In this situation, the temperature of the exhaust air would be as high as possible. As will be shown later, a very good location for the insulation in a full pressure suit assembly is external to all of the layers of moving air and external to the impermeable shell of a pressure suit as well.

DESCRIPTIONS OF VENTILATING GARMENTS

Several ventilating garments are described below in order to illustrate the evolution and application of some of the principles presented above—especially those applicable to distribution of supply air.

Many early ventilating suits used a system of narrow tubes to distribute the air from a central point. A central inlet hose, from which radiated ten or more lines, carried supply air. Each small line was taken to a point on the body surface where the air escaped. This arrangement insured an even airflow by virtue of a high and equal resistance in each of the narrow tubes, as long as these tubes were the same length or their high resistances adjusted if the lengths were unequal. The overall resistance of such a system was quite high Also, the air which was delivered came out at a relatively small number of points. An improvement came in suits which employed flat ducts as opposed to narrow pipes for delivery of air. Here the over-all resistance was less, but distribution was still limited to a few points on the body surface. Figure 5 shows such an experimental arrangement, where flat ducts carry the air across the body and the air escapes from a line of holes on the surface next to the skin.

Figure 6 is a photograph of the first version of the Air Force ventilating garment, later designated Type MA-1, originated by H. A. Mauch. It is described in a WADC Technical Report.[1] This represents a tremendous improvement over tubes and flat ducts, in that air is delivered in a thin sheet between two layers of impermeable material. The impermeable layers are kept apart by a loose spacer material. which offers little resistance to air movement. Air escapes through very small holes in the inner layer at hundreds of points. By this means the supply air reaches the wet skin at many points and causes evaporation over much of the body surface. This ventilating garment also employs large holes which traverse both layers. When the suit is inflated, the area around the large holes forms a sort of dome over the skin. Air escaping from the small holes in the roof of the dome escape in high-velocity jets which are meant to produce turbulent airflow, and therefore good evaporation and heat transfer. There are other small holes in the inner layer at sites between the domes.

Figure 5. A laboratory version of a ducted air supply for ventilated clothing, including a coverall made of plastic spacer material.

Figure 6. (above) The original
double-layered Air Force venti-
lating garment, Type MA-1,
designed by H. A. Mauch.
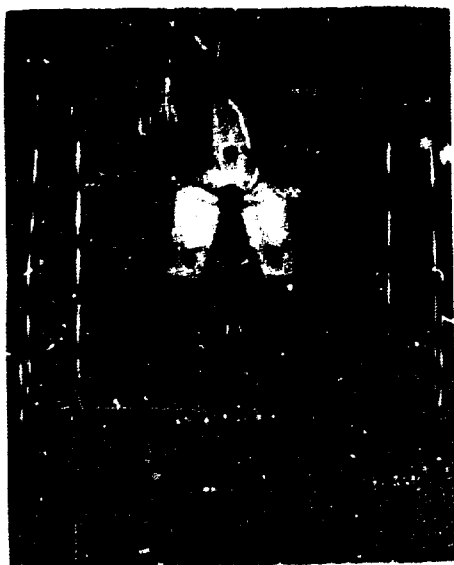
Ventilation of tight-fitting garments, such as
the MC-3 and MC-4 partial pressure suits, which
cover the torso with an impermeable pressure
bladder, underscored the problem of providing a
proper exhaust pathway. A ventilating garment
was placed next to the skin to evaporate sweat but,
in order for airflow to occur in a uniform fashion,
an even unhampered supply and return pathway had
to be provided. The solution came through having
the entire inner layer of basket-weave vinyl pressed
evenly against the underwear. The resistance at all
the small holes was then approximately equal. In
this situation, the domes and jets did more harm
than good, in that some air was apparently escaping
before gaining its proper load of moisture. Figure
7 is a photograph of the vest-sized garment, desig-
nated Type CMU-1/P, now used in ventilating MC-3
and MC-4 partial pressure suits.

Figure 8 is a photograph of the current,
general-purpose ventilating garment (Type MA-3),
which embodies the basket-weave vinyl, the lack of
domes, extra inner spacer to insure free passage
within the double layer, and tie tapes to insure
fairly close fit of the ventilating garment around
the subject.

Figure 7. (above) Special double-layered
plastic ventilating garment, designated
Type CMU-1/P, for use with partial
pressure suits, Type MC-3 and Type
MC-4.

Figure 8. (left) A current, full-body,
Air Force ventilating garment, desig-
nated Type MA-3.

The most recent problem in ventilation has been the proper ventilation of a close-fitting, lightweight, impermeable pressure suit. This garment covers the wearer completely and would be uncomfortable and dangerous if ventilation is not included. The light weight of the garment assembly and its close fit are desirable from the standpoint of wearability and lack of restriction of movement, but these same features add to the difficulty of proper ventilation.

The difficulty of ventilating a full-pressure suit assembly comes from its being the first clothing assembly in which it was necessary to be aware of every one of the principles of air distribution, evaporative effectiveness, and best use of convective cooling. Earlier clothing assemblies—such as anti-exposure suits, heavy flight clothing, and MC-3 type partial pressure suits—had certain of the distribution pathways inherently present, so that it was difficult to be aware of the importance of all of them. In the lightweight, full-pressure suit assembly, every segment of the air distribution pathway had to be considered, proper spaces insured, insulation placed in the right layer, and so forth. In the next section, the effect of each of the major design principles is clearly shown in comparative experiments.

A complete ventila ng system under a lightweight, close-fitting, impermeable pressure shell includes: a low-resistan ribution pathway for supply of air, uniform opportunity for escape of air into the active layer, a return pathway which is of low resistance everywhere and which lies external to the preceding two layers, and insulation located external to all. Such a system is indicated schematically in cross section in figure 9. A garment assembly of this construction was made at the Aero Medical Laboratory and subjected to empirical test. In fact, a series of garments was made, so that each of the major principles discussed was tested and its effect measured on the performance of the whole assembly. Demonstration of the validity of this approach is the subject of the next section.
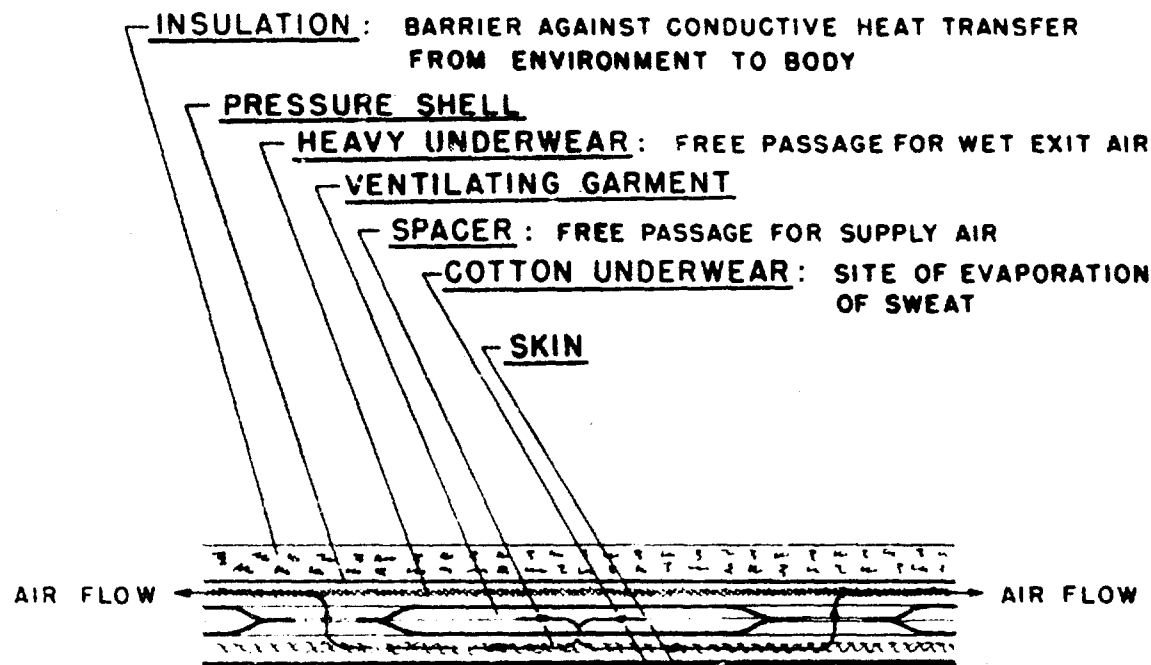

Figure 9. Schematic representation of the layers required for a complete ventilating system used with a full pressure suit.

EMPIRICAL TEST OF PRINCIPLES

A series of experiments was done in which the ventil . ing a. sembly for a lightweight pressure shell was built up layer by layer. In each configuration, subjects were exposed to a standard heat stress. The chamber temperature in all experiments was 165° F., air and wall temperature. Ventilating air was delivered with a temperature of 85° F., a humidity of 6 mm. Hg vapor pressure, and a flowrate of 10 cubic feet per minute. The subject was sitting and engaged in light activity.

Experiments were continued until a physiological tolerance limit was reached. The tolerance point has been described previously[2,3] and is a state which is termed "impending heatstroke." The subject in this state has a high and rising rectal temperature, a very rapid, full pulse, flushed skin, diminution or cessation of sweating, and various mental symptoms—such as loss of attention, compulsive restlessness, headache, or mild nausea. From long experience, the medical observer knows to stop just short of the condition which would result in loss of consciousness and a serious clinical heatstroke. This end point of impending heatstroke has been found one of the most reliable indices used at this laboratory. The time required to reach this state has excellent comparative value.

In table I, results of these experiments are listed. Along with the time to reach tolerance are other indices used to describe the state of the subject at the end of the experiment:

The index of strain has been used in previous reports in this laboratory.[1,2,3,7] It is the algebraic sum of terminal pulse rate/100, sweat rate, and rate of change of rectal temperature.* The rate of change in rectal temperature is a useful index by itself. It has been found to correlate well with the index of strain, and with the "body storage index" as used at UCLA. The ratio of sweat evaporated to sweat produced, E/S, is particularly informative in this sort of evaluation. The ratio is derived by dividing the amount of sweat evaporated by the total amount of sweat produced. It is, in effect, a measure of the efficiency of evaporation of the ventilating system.

It can be seen in table I that the basic light assembly is hard on the subject. The tolerance time of 45 minutes is not much greater than expected for an unventilated subject in similar clothing In the next entries improvement results from the successive addition of spacer material to provide low-resistance pathways. Tolerance time, index of strain, change in rectal temperature, and the E/S ratio all improve as uniform distribution and return of ventilating air are insured by proper placement of spacer materials. The last two assemblies in table I show the effect of adding insulation over the pressure shell. The next to the last garment assembly does not include all of the spacer finally decided upon, but does include insulation. The last garment assembly includes all of the principles discussed in this report. The time of 180 minutes, or 3 hours, is not in this case a tolerance time. The subject was still relatively comfortable, while the index of strain showed moderate or moderately severe physiological strain. Notice also that the E/S ratio is highest in this final assembly. Actually, in this case, the production of sweat by the man in response to that standard heat stress was considerably less than in any of the previous experiments. Probably less heat was reaching him. At the same time, that sweat which was produced was evaporated effectively.

It might be possible to attempt to make a quantitative evaluation of the effect of each of the various principles, using the data in table I. On the other hand, the experimental experience is somewhat limited, and it seems more appropriate to present it as qualitative confirmation of the effect each principle has on the whole assembly.

The effectiveness of the final ventilating system, which was constructed to include all of the layers shown in figure 9, was better than any other system tried for full pressure suits. This final assembly in the full pressure suit gave as good heat protection as is obtained by good ventilating systems in other types of clothing.

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* This index will yield values close to 1.0 at the warmer levels of comfort. Higher values indicate relative severity of the physiological strain.

TABLE I

EFFECTS OF HEAT EXPOSURE IN SEVERAL VENTILATED, PRESSURE-SUIT ASSEMBLIES

(air and wall temperatures: 165° F.; ventilating air: 10 c.f.m. at 85° F. and 6 mm. Hg vapor pressure)

Type of Assembly	Time To Reach Tolerance (in min.)	Index of Strain*	Rectal Temperature (° C./hr.)	E/S#
Basic (light cotton underwear, double-layered ventilating garment, light impermeable pressure shell, attached leather gloves and helmet, leather boots)	45	4.1	1.5	.30
		(average of three experiments)		
Basic, plus spacer material over ventilating garment, but under pressure shell	90	2.9	0.7	.45
		(average of three experiments)		
Basic, plus spacer materials under and over ventilating garment	125	2.4	0.7	.72
		(one experiment)		
Basic, plus spacer material over ventilating garment, plus insulation over pressure shell	140	2.2	0.5	.56
		(average of two experiments)		
Basic, plus spacer materials under and over ventilating garment, plus insulation over pressure shell	180**	1.8	0.2	.75
		(average of two experiments)		

* For explanation, see text # For explanation, see text

** These runs were not tolerance runs, but terminated for convenience after 3 hours.

DISCUSSION AND RECOMMENDATIONS

During the several years of experience with ventilating garments, two general policies have emerged—one concerning the efficient use of energy for ventilation, and the other concerning the need for care when garment assemblies are combined or integrated together.

The ventilation systems which have been described have low resistance to airflow—only 2-4 inches of water backpressure at 12 c.f.m. of air at 1 atmosphere. In view of the severe limitation of the available power in certain aircraft of the future, it is important to keep the resistance or backpressure of ventilating garments as low as possible. No improvement in effectiveness occurs with a high-resistance distribution system. Unless a clear gain could be shown for a high-resistance, high-backpressure system, it would seem wrong to design any system other than one with the lowest possible energy requirement.

During the developments described earlier, especially the search for a successful means of ventilating a full pressure suit, errors have been made because of a great desire to integrate or combine protective garments into one suit. Over-integration can be dangerous. Excessive

combining can compromise the functions of the individual protective garments which make an integrated assembly. Sometimes this may be avoided, and sometimes, also, improvement in a given function is gained when that function is combined with several others.

Another problem caused also by over-integration is that the final garment lacks flexibility in the sense that it cannot be worn so that it has only some of the protective functions. It is very often desirable to be able to wear two out of a possible five protective garments, or three out of five, or two out of four—whatever combination is appropriate to the mission to be flown. A plea is made to integrate protective garments judiciously.

Keeping in mind these general policies to obtain economy and flexibility in garment design, and recalling the useful principles described in earlier sections, it is recommended that:

    a. Ventilation of clothing be undertaken as a useful aid in designing multi-purpose protective clothing, or any clothing which must be worn in heat, which by its nature reduces the effectiveness of physiological mechanisms for heat loss.

    b. The design of ventilated clothing be tailored to the particular requirements of the complete clothing assembly, using the principles presented in this report, which may be restated now as follows:

        1. Air is distributed over a large body surface with uniform delivery at all points.

        2. Air is permitted to pass slowly and thoroughly through the area where evaporation takes place.

        3. A free and uniform return pathway is provided for air from every point.

        4. Returning air is conducted to the escape point in a layer external to the supply and actively cooling layers.

        5. Insulation is placed external to the air-ventilating system

        6. The total resistance in the ventilating circuit is kept as low as possible.*

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* In the Appendix is presented a brief theoretical treatment of work done in ventilating through high-resistance and low-resistance pathways.

BIBLIOGRAPHY

1. Mauch, H. A., J. F. Hall, and F. K. Klemm. A Ventilated System for Clothing, WADC TR 55-152, April 1955.

2. Webb, P. Ventilated Clothing as a Protection against Heat Exposure, American Society of Mech. Engrs. Aviation Conference, Paper No. 56-AV-4, 1956.

3. Webb, Paul, and James H. Veghte. Several Variables Affecting Performance of Ventilated Clothing, WADC TR 56-43, January 1956.

4. Skilling, Donald C., Joseph W. McCutchan, and Craig L. Taylor. A Quantitative Investigation of the MA-1 Ventilating Garment when Used with a Modified MK-IV Anti-Exposure Suit, WADC TR 56-209, December 1956.

5. Greider, Herbert R., and Louis J. Santa Maria. "Subjective Thermal Comfort Zones," J. Aviation Medicine, 28: 272-276, 1957.

6. Veghte, James H. The MA-2 Ventilating Suit as a Protective Garment in Cold, WADC TR 57-564, September 1957.

7. Veghte, James H., and Paul Webb. Clothing and Tolerance to Heat, WADC TR 57-759, December 1957.

APPENDIX

A DISCUSSION OF SEVERAL ASPECTS OF FLUID MECHANICS
PERTINENT TO THE DESIGN OF CLOTHING VENTILATION SYSTEMS

by Jeremy F. Crocker, 1/Lt., USAF

Introduction

This appendix discusses the limitations placed on the performance of air supply blowers by ventilating garment and hose systems which are designed in such a way that high pressures are required to force the necessary flow of air or gas through the garment. As a guide to the designers of these systems, it also describes the physical basis of flow through tubes and orifices, in order to point out the dimensions which are influential in reducing pressure loss.

Summary

1. Operation of ventilating garments from presently feasible lightweight, compact blowers demands limitation of the pressure drop in garment and supply hose to less than 2% of the absolute pressure. Design of higher pressure blowers is fundamentally limited by increase in power consumption and by compression heating of the gas stream.

2. In the design of ventilating garments for minimum pressure drop, the following factors should be considered:

    a. In tubes carrying equal rates of flow, pressure loss is proportional to the fifth power of the diameter, so that a tube only one-third smaller in diameter than another will have seven times the pressure loss.

    b. Pressure drop across an orifice where no pressure recovery occurs is an approximately hyperbolic function of the ratio of restriction diameter to normal diameter, so that pressure loss for a 0.3 ratio is ten times that for a 0.7 ratio.

3. All pressure losses in the hose and garment system are proportional to the gas density, so that pressure losses at altitude are reduced in proportion to the absolute pressure.

Derivation

1. Blower Performance — For small increases in pressure, the power absorbed in the compression of a flow of gas is related to the pressure increase by the following equation, derived from the general energy (Bernoulli's) equation for an ideal fluid:

$$P = Q \, (p_2 - p_1) \qquad\qquad (1)$$

where P is power $(\frac{ft.-lb.}{sec.})$

    Q is volume flow $(\frac{ft.^3}{sec.})$

and p_1 and p_2 are the pressures at the inlet and the outlet of the blower, respectively $(\frac{lb.}{ft.^2})$

Since a blower is not perfectly efficient, the power which must be supplied to drive it is larger that that given above, and reflects the efficiency of the blower as follows:

$$P' = c_1 \frac{P}{e} = c_1 \frac{Q(p_2 - p_1)}{e} \qquad (2)$$

where P' is electrical power (watts)

e is the over-all efficiency of the blower-motor combination (decimal)

and c_1 is the conversion factor from $\frac{ft.-lb.}{sec.}$ to watts (1.356 $\frac{watt-sec.}{ft.-lb.}$)

The efficiency of some small blowers is quite low. An example is the present Air Force standard blower[1] for ground and in-flight clothing ventilation, which can be used to supply either one or two ventilating garments. Its maximum efficiency, which occurs at a flowrate and pressure rise very near that resulting from the connection of two MA-2 garments, is 0.124 (12%). At lower flows, the efficiency is also lower. With only one garment connected and the other outlet closed, the efficiency is only 0.07 (7%). The severe rate at which electrical power requirements increase when pressure rise is increased is illustrated in figure 1.1, which shows also how low efficiencies act as a multiplier of power requirements.
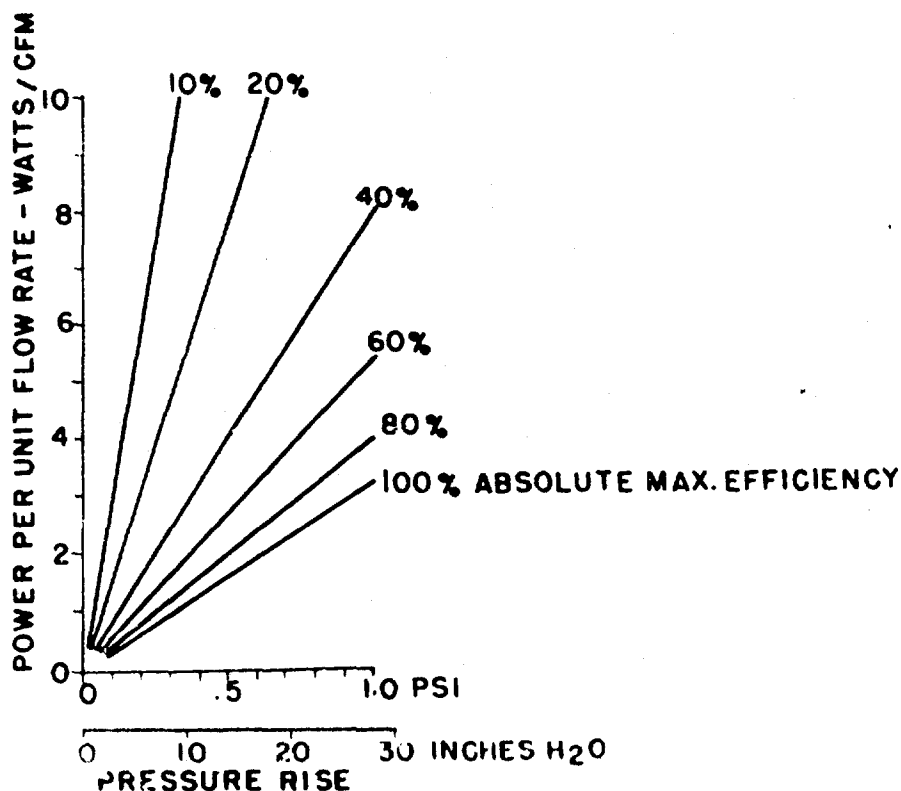

Figure 1.1. Rate at Which Electrical Power Requirements of a Blower Increase when Pressure Rise Is Increased.

In addition to efficiency, the element of weight is also affected by pressure rise. For instance, at sea level the maximum pressure which the axial vane blower described above can produce is 0.3 pound per square inch (8 to 9 inches of water). When higher pressures are required, it becomes necessary to either increase speed or to use more complex types of machinery (multistage axial vane, positive displacement rotary, or reciprocating compressors). Increasing speed generally means increasing noise and friction losses, and decreasing reliability, and thus has limits. At a given speed, increasing pressure rise means increasing internal pressure and rotor torque, which breeds increases in wire gage, magnetic core mass, and rotor diameter in the electric motor. All of these increases have the common property of increased weight, and, when the blower is to be used in high-performance aircraft, weight can be translated directly into performance decrements.

Finally, pressure rise in a blower is accomplished by a process of nearly adiabatic compression, which unavoidably results in an increase in air temperature. This is important (10° F. for a 1 p.s.i. rise at sea level) in even a perfectly efficient blower, but is multiplied when efficiency is low. This temperature rise can be severe enough to counteract by conductive heating the evaporative cooling ability of the ventilating garment when worn by an aircrewman, particularly in a hot, damp climate.

2. Fluid Flow through Tubes and Orifices. — The major portion of pressure drop in some ventilating garments has been caused by small-diameter tubes and tight restrictions in fittings. An example is one which required a pressure of over 15 pounds per square inch for a flowrate of 10 cubic feet per minute. In this case, more than 95% of the pressure drop occurred in tubing and fittings. Factors causing pressure drop are discussed below, in order to guide designers of ventilating systems in avoiding high resistance.

a. Tubes. — A flow of fluid of given density through a tube at a given volume flowrate is maintained by a certain pressure gradient along the tube. The pressure gradient required can be expressed by the following relationship, known as the "pipe friction" equation:

$$\frac{dp}{dl} = f \left(\frac{\rho V^2}{2 g_c D} \right) \tag{3}$$

where $\frac{dp}{dl}$ is the pressure gradient ($\frac{lb.}{ft.^2}$ per ft.)

f is the "friction factor," which is an empirical function of tube roughness and Reynolds number. (In the fully developed turbulent flow typical of clothing ventilation supply hoses, this factor f is effectively constant over a wide range of Reynolds numbers.)

ρ is density ($\frac{lb.}{ft.^3}$)

V is average velocity ($\frac{ft.}{sec.}$), defined equal to $\frac{Q}{A}$, where A is the cross-sectional area (ft.^{2})

D is tubing diameter (ft.)

g_c is a dimensional constant equal to 32.17

Now, substituting the defined value for V into equation (3), and letting A equal $\frac{\pi D^2}{4}$, gives:

$$\frac{dp}{dl} = \frac{f \rho}{2 g_c D} \left(\frac{4Q}{\pi D^2} \right)^2 = \frac{8 f \rho Q^2}{\pi^2 g_c} \left(\frac{1}{D^5} \right) \tag{4}$$

Equation (4) implies that the pressure gradient is inversely proportional to the fifth power of the diameter. The impact of this can be seen by comparing two tubes carrying equal flows of equal density. If the diameter of one is two-thirds the diameter of the other, the pressure drop in this tube will be three-halves to the fifth power, or 7.6 times as much. If blowers of equal efficiency were supplying these hoses, the blower for the smaller hose would require over seven times as much wattage as that for the larger.

b. Orifices.——When a fluid flows through an orifice which is followed by a gradual enlargement, pressure losses may be quite low compared to those which occur when the enlargement is abrupt and turbulent mixing occurs. But when considerations of size and convenience of a fitting, such as a connector, make a short restriction seem desirable, these same considerations usually preclude providing an enlargement as gradual as necessary (cone with 14° or less vertex angle). Prevention of large pressure losses therefore demands avoidance of severe restrictions. Knowledge of the laws relating pressure loss to the geometry of restrictions will aid the designer in deciding what constitutes a severe restriction.
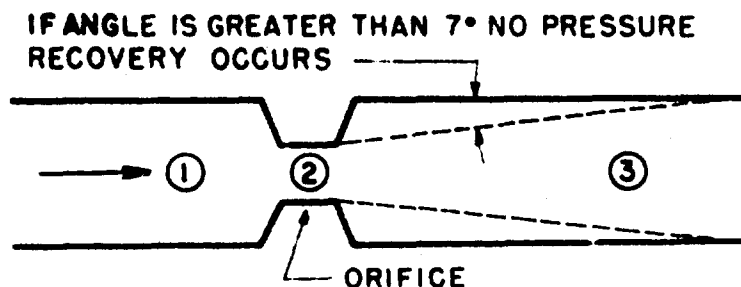

Figure 2.1. Nozzle Consisting of Orifice and Divergent Section.

Consider the nozzle shown in figure 2.1. Bernoulli's equation for an ideal fluid relates pressure decrease between points 1 and 2 to velocity increase and applies with small error to real fluids such as air. However, unless a gradual enlargement (dotted lines) is provided, this loss of pressure will not be recovered when the velocity is reduced again in the tube downstream from the orifice. Thus, the pressure at 3 will be the same as that at 2, and the pressure decrease between 1 and 3 will be given by the momentum equation as follows:

$$p_1 - p_2 = \frac{\rho(V_2 - V_1)^2}{2g_c} \qquad (5)$$

where $p_1 - p_2$ is the pressure loss $(\frac{lb.}{ft.^2})$

Since $V = \frac{Q}{A}$, this equation can be transformed as follows:

$$p_1 - p_2 = \frac{\rho Q^2}{2g_c} \left(\frac{1}{A_2} - \frac{1}{A_1}\right)^2 \qquad (6)$$

and, if the tube upstream and the restriction are circular in cross-section (or nearly so) their cross-sectional areas will be $\dfrac{\pi D_1^{\,2}}{4}$ and $\dfrac{\pi D_2^{\,2}}{4}$. Substituting these in equation (6) gives:

$$p_1 - p_2 = \frac{8\,\rho Q^2}{\pi^2 g_c}\left(\frac{1}{D_2^{\,2}} - \frac{1}{D_1^{\,2}}\right)^2 = \frac{6\,\rho Q^2}{\pi^2 g_c D_1^{\,4}}\left(\frac{D_1^{\,2}}{D_2^{\,2}} - 1\right)^2 \qquad (7)$$

This pressure loss is not as easy to calculate as the fifth power relationship for tubes, and thus it has been plotted in figure 3.1 as a dimensionless function of the ratio of orifice diameter to tube diameter ($\dfrac{D_2}{D_1}$). Pressure loss can be obtained directly from this graph by using the known values of p, Q, and D to calculate the group:

$$\left(\frac{\pi^2 g_c}{8}\right)\frac{D_1^{\,4}}{\rho Q^2} = 39.70\ \frac{D_1^{\,4}}{\rho Q^2} \qquad (8)$$

Figure 3.1. Pressure Loss as a Dimensionless Function of the Ratio of Orifice Diameter to Tube Diameter